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INTERACTION STUDIES OF LASER BEAMS INTERSECTING IN AN ACTIVE MEDIUM
(Crossed Beam Laser)

Second

Semi-Annual Technical Summary Report

1 August 1966 - 31 January 1967

ONR Contract No. Nonr-5034(00)
Project Code No. 4730
ARPA Order No. 306

Prepared for

Office of Naval Research
Department of Navy
Washington 25, D.C.

Prepared by

Research and Development Center
General Electric Company
Schenectady, N.Y. 12301

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Section I

SUMMARY

A brief experiment was carried out employing two Q-switched laser beams interacting in an optically pumped Nd doped glass in a regenerative configuration. Interaction effects were observed but no attempt has yet been made to analyze these effects.

The experimental setup was then modified to investigate interaction and energy transfer effects in an amplifying configuration. The energy transfer process is initiated by passing an intense, spectrally narrow Q-switched laser beam through an optically pumped amplifier rod; the energy transfer taking place in the amplifier rod is observed by simultaneously passing a low level, spectrally wide probe beam through the amplifier rod. By using a spectrograph and a time-resolved image converting camera, the amplified probe signal is measured as a function of wavelength and time. Calculations indicate that the population inversion density in the amplifier rod should be about 1 joule/cm^3, and the Q-switched laser beam output should be about 1.5 joules (for room temperature measurements) to significantly alter the gain of the amplifier rod.

A desirable probe beam is one with an output that is a smooth and continuous function of time and wavelength. After several methods were tried a smooth output was obtained, however the probe signal was not intense enough for streak photography. A sufficiently intense probe beam was produced using a normal pulse laser. It has an output duration of 0.5 msec and laser spikes that occur randomly in time but at selected regularly spaced wavelengths. Many streak photographs were taken to observe the temporal behavior of these spikes to ascertain their common characteristics. A Jarrell-Ash densitometer was converted to aid in the analysis of the streak photographs.

A perturbing Q-switched laser beam was assembled having a Fabry-Perot cavity containing a saturable dye in series with a Kerr cell.

Section II

WORK PERFORMED

A. REGENERATIVE INTERACTION EXPERIMENT

A short experiment was performed in the regenerative configuration (see First Semi-Annual Technical Report) in which both of the intersecting Fabry-Perot cavities had Eastman Kodak Q-switch solution #9740 inserted in small 0.5 cm thick spectroscopic cells. The optical axes of the two Q-switched laser cavities were set at 5 degrees from one another. Several observations were made.

If one of the Fabry-Perot cavities is blocked with an opaque card, the other Q-switched cavity would produce an output beam with an energy of E_1. If both Fabry-Perot cavities are allowed to Q-switch, then the energy output of one of the two beams was always greater than E_1. The Fabry-Perot cavity that Q-switched with the more intense pulse caused the other Fabry-Perot cavity to produce a pulse with reduced amplitude. Under the same pumping conditions the amplitude reduction would occur in either cavity probably depending upon which cavity started to Q-switch first. These observations indicated that up to a 50% difference in output energy between the two Fabry-Perot cavities could occur when they were simultaneously sharing the same active medium. No interpretations of the type of coupling have as yet been attempted.

B. INTERACTION AMPLIFIER EXPERIMENT

1. System Considerations

The concept of the interaction amplifier experiment is to use an intense, spectrally narrow perturbing laser beam to alter the gain characteristics of a pumped Nd doped glass laser amplifier rod. Simultaneously, a low intensity probe beam is passed through the laser amplifier, and the measured increase in intensity of this probe beam as a function of wavelength is directly related to the gain of the amplifier. By measuring the gain as a function of time and wavelength during

an interval which encompasses the perturbation event, energy transfer rates can be obtained which can be used to substantiate a theoretical model for the energy transfer process.

In order to aid in the determination of the coupling mechanisms and rates of energy transfer, measurements can be made as a function of neodymium doping concentration and interaction amplifier rod temperature. If the energy transfer takes place in a few nanoseconds[(1)] at room temperature, the transfer time should be longer at a lower temperature and hence should be easier to measure. These interactions and their measurement impose certain performance requirements on the components of the experimental system. The component requirements are considered in the following discussion.

To measure the gain of the interaction amplifier laser rod as a function of time and wavelength at a wavelength of approximately 1.06 microns a one-meter Czerny-Turner spectrograph with a high speed image converting camera is available for use. This camera has a potential resolution of a fraction of a nanosecond if enough light is available for the measurement. Initially, data on the sensitivity of the streak camera was not available. Although estimates of the streak camera sensitivity were made from resolution data measurements with a xenon lamp illuminator, these were not very accurate. Therefore the streak camera was attached to the spectrograph and measurements of the power required were made. To obtain usable photographs at a 2.5 mm/nanosecond streak rate which is the fastest rate available, an input peak power of 7 kilowatts is required at a 1.06 micron wavelength to the spectrograph. To streak at a slower rate (0.1 mm/nsec) with a resolution of 1.0 nanosecond, 250 watts of power is required. With a knowledge of the power required for the streak camera the design specifications for the probe beam laser can be calculated.

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1 J. Boyden, 1966 International Quantum Electronics Conf., Phoenix, Arizona, April 1966, Paper #8B-8

The probe laser beam must be intense enough to yield usable streak photographs but weak enough to cause negligible perturbation to the interaction amplifier rod. The spatial diameter of the probe beam passing through the amplifier rod should be slightly smaller than the diameter of the perturbing beam to allow for possible errors in misalignment. The pulse length of the probe beam should be at least twice that of the perturbing beam.

The most straightforward way to generate the required probe laser output is a typical normal pulse laser. However, the output of a typical normal pulse laser contains "spikes" of laser power which are distributed randomly in time and wavelength. This causes measurement problems because with one streak camera it is not possible to measure the probe beam both before and after it passes through the interaction amplifier rod. Therefore, the initial portion of the probe beam has to be extrapolated through the perturbation and cross-relaxation periods in order to analyze the interaction effect. In order to avoid this requirement of extrapolation, it is preferable to have a probe beam without spikes. Several possible methods have been reported by which the laser output spikes have been eliminated.[2,3,4] A number of these methods produced a satisfactory probe beam.

In order to perturb the interaction amplifier in a manner which has the possibility of yielding energy transfer effects, a perturbing beam should be spectrally narrower than the homogeneous linewidth of the amplifier rod. Further if the energy transfer is as fast as certain workers have reported[5] the perturbing pulse must be well defined in time. Thus a Q-switched laser beam was selected for the perturbing beam. It is necessary to know how much energy in

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2 C.G. Young, et al, J. Appl. Phys. 37, 4319 (1966)

3 R.V. Ambartsumyan et al, Sov. Phys. JETP 24, p. 41 (1967)

4 E. Snitzer, "Fiber Optic Laser", Final Technical Report, USAROD Rep. No. 3209 (1965)

5 Boyden, Op. Cit.

the Q-switched pulse is required to saturate the gain of the interaction amplifier at the wavelength of the "hole-burning" Q-switched pulse. A simple calculation of when saturation occurs is to calculate the amount of energy which, if multiplied by the gain of one centimeter of the amplifier path, would be equal to the stored energy.[6] This calculation yields an approximate value which should be within 10% of the exact value. If one further assumes that very little cross-relaxation occurs during the Q-switched pulse, then an intense, spectrally narrow (much less than the homogeneous linewidth) Q-switched signal should remove 1/e of the stored energy in the homogeneous linewidth. Using these two assumptions, 1.5 joules output from a Q-switched laser will be needed to saturate the 0.5" diameter interaction amplifier rod at room temperature, and 0.7 joules will be needed at liquid nitrogen temperature.

The interaction amplifier rod is required to have sufficient gain (or population inversion) in order to provide a discernible difference in output signal when the interaction occurs and is recorded by the spectrograph and streak camera. It is expected that a 5 dB small signal gain through the amplifier should be adequate for this purpose. Using American Optical AOLux Type 0835 laser glass 6" long with a gain characteristic of 1/3 dB/cm per J/cm^3 of inversion, the required population inversion density should be 1 J/cm^3.

For room temperature measurements a water-cooled helical-lamp pump cavity for the interaction amplifier was built and described previously (see description in First Semi-Annual Report). A new cryogenic laser pump cavity had to be designed which could cool the interaction amplifier rod down to 77°K.

Another requirement on the system is that the principal portion of the Q-switched beam cannot be allowed to strike and enter the spectrograph. This direct Q-switched beam would burn the entrance slits to the spectrograph, and it would saturate the streak camera image converting tube by at least 3 orders of magnitude

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6 C.G. Young and J.W. Kantorski, Appl. Optics 4, 1675 (1965)

which might cause permanent damage to the tube face. Provisions have been made to have the Q-switched perturbing beam angled just enough to impinge on a diffuse reflector positioned adjacent to the spectrograph entrance slit. A fiduciary mark of the Q-switched beam will appear on the streak photograph, and this will be part of the component of the Q-switched beam which is scattered by the amplifier rod.

2. Component Development

Probe Beam

As mentioned in the preceding section on Systems Considerations, attempts were made to obtain a spikeless output from the probe laser. The first of these methods was suggested by work in a report by Snitzer[7] where he observed that certain clad Nd-doped glass laser rods would lase without spiking. Two different 1/2" x 6" clad rods (American Optical Type 3935-C and 0835-C) were tried with different Fabry-Perot geometries and values of Q. Certain combinations of these yielded a photodetector output that appeared spikeless. However, when this beam was analyzed by a time resolved spectrograph, it was found to be full of spikes at various wavelengths that add up to a smooth distribution if they are integrated over all wavelengths.

Since two clad rods and an additional pump cavity were available it was decided to try a fluorescent probe whose output would certainly be a smooth function of time and wavelength.[8] Using the sensitivity of the streak camera system and calculating the solid angle which could pass through the interaction amplifier and into the f/7 aperture of the spectrograph it was determined that close to 40 dB of gain would be required to achieve usable exposure levels on the streak camera photographs. If the two probe laser rods and the interaction amplifier rod shown in Fig. 1a were pumped at their respective maximum flashlamp

7 Snitzer, Op. Cit.

8 Young, et al, Op. Cit.

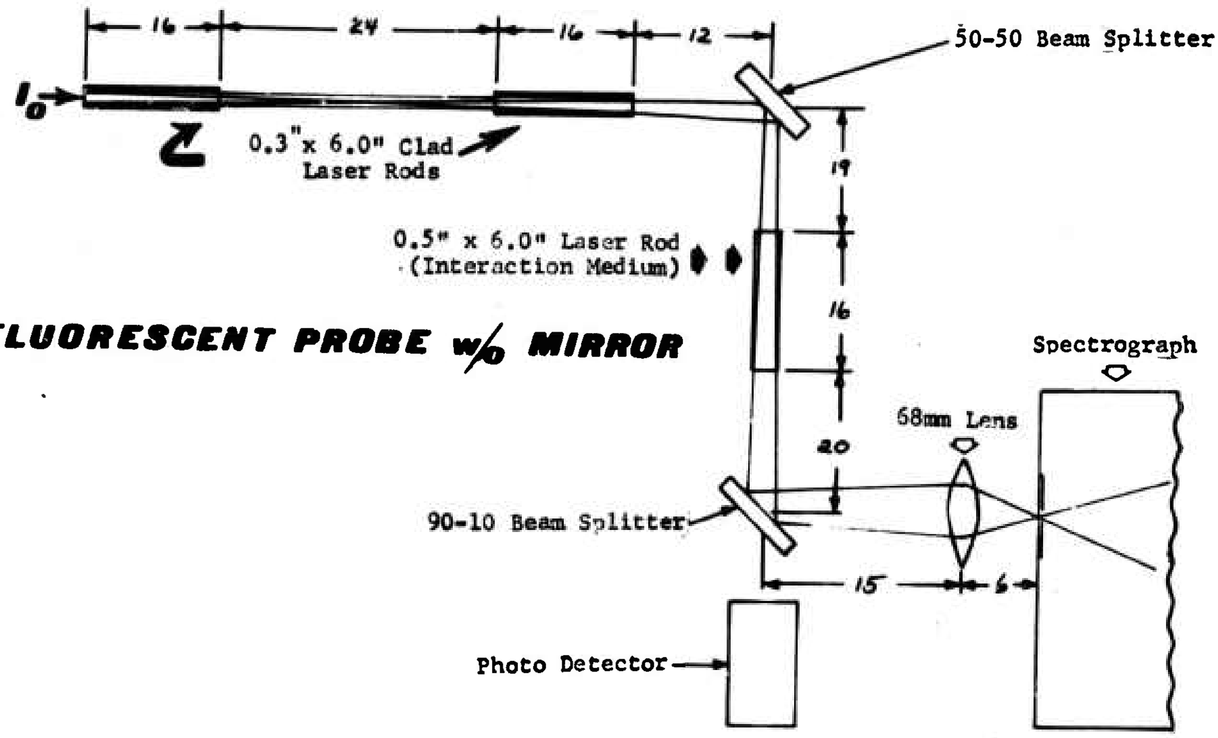
energies it was hoped their gains might approach the 40 dB required. It was found that the gain could not be pushed above 30 dB without flashlamp damage. Since no additional laser pump systems were available for this program, a mirror was placed on the back of the probe lasers as shown in Fig. 1b, in an effort to increase the intensity of the existing probe. The mirror with its 1-meter radius had a collimating effect on the fluorescence output and effectively doubled the gain of the two probe rods. It was expected this mirror could be tilted slightly to keep the entire system from breaking into laser oscillations, but lasing was observed at all usable angles of tilt.

Next, an attempt was made to duplicate the work of Ambartsumyan, et al[9] in which they replaced the 100% specular reflector in a typical normal pulse laser with a 100% diffuse reflector and obtained a spikeless output. The diffuse reflector should produce extensive mixing of the Fabry-Perot cavity modes to eliminate the laser spikes. The probe laser mirror shown in Fig. 1b was replaced with a 100% diffuse relfector and a 95% specular output mirror was placed at the output of the probe laser. Unfortunately the scattering loss from the diffuse reflector was so high that lasing threshold could not be attained.

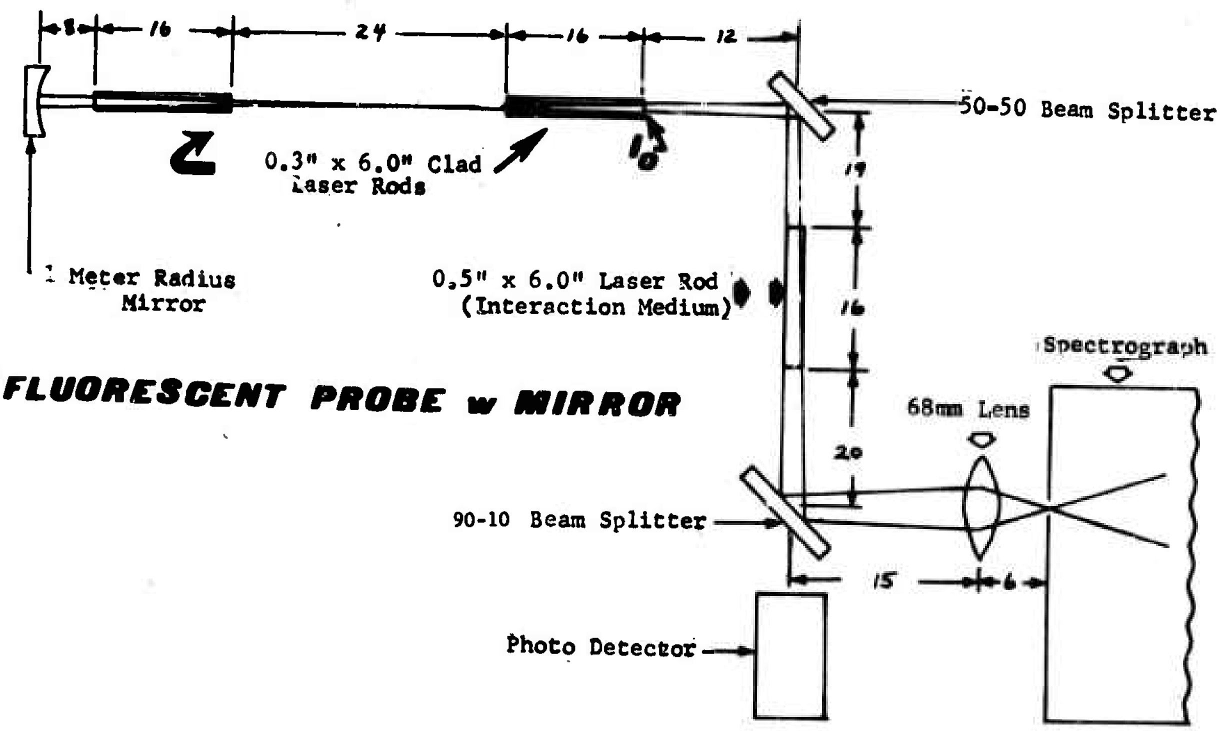
Another method was tried which was suggested by the above work. Between the two clad rods, two tipped ground glass plates were inserted, each of which were tipped 5° off the optical axis in a direction perpendicular to each other. It was hoped that the small angle forward scattering of these plates would produce mode mixing similar to the above experiment but with a far lower cavity loss. Indeed this configuration lased with only a 20% increase in threshold; however the small angle forward scattering did not significantly reduce the spiking behavior.

Finally it was decided to make the best possible use of a normal pulse probe with its inherent spiking behavior. Glass etalons were used as the output Fabry-Perot reflector as shown in Fig. 2 which allowed the spikes to occur only at

9 Ambartsumyan, et al, Op. Cit.



1a. ***FLUORESCENT PROBE w/o MIRROR***

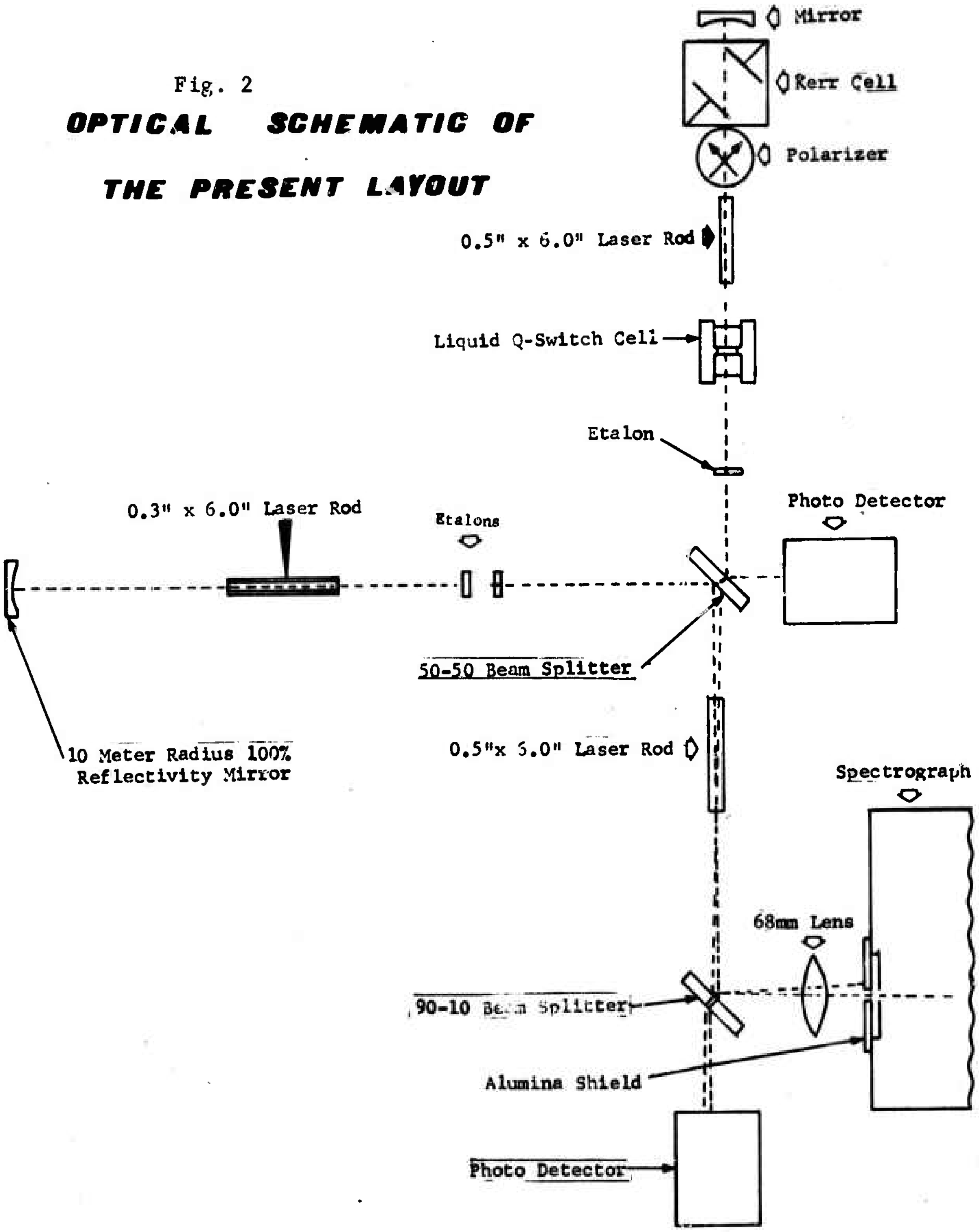


1b. ***FLUORESCENT PROBE w MIRROR***

Fig. 1. Fluorescent Probe Configurations

Fig. 2

OPTICAL SCHEMATIC OF THE PRESENT LAYOUT



certain regularly spaced wavelength intervals. With this type of probe pumped at more than 3 times threshold to produce a high density of spikes, streak photographs were taken and are reported in Section 3.

Perturbation Beam

A Q-switched laser for the perturbation beam was assembled having an electro-optical Kerr cell, a Glan-Thompson polarizer, and a cell containing Eastman Kodak Q-switch saturable dye solution #9740. Saturable dyes have been employed to reduce the spectral output width of Q-switched lasers.[10]

Interaction Amplifier

The water-cooled cavity used as the interaction amplifier pump cavity has been described in detail in the First Semi-Annual Technical Report. It has been possible to optically pump the interaction amplifier rod to achieve a population inversion density of about 1 J/cm^3; this should provide a small signal gain of about 5 dB as desired.

To construct a liquid nitrogen cooled amplifier pump cavity it was decided to enclose the rod in a cylindrical dewar with controlled leak chambers at both ends of the rod which would maintain a nitrogen atmosphere -- the rod ends as well as both faces of the transmission windows as shown in Fig. 3. A mock-up of the seal geometry was constructed and several seal designs were tested. The only seal which would contain the liquid nitrogen was a combination of Kel-F and Invar tapered rings whose differential expansion increased the sealing forces as the temperature was lowered.

After this seal was successfully tested with a laser rod, a final liquid nitrogen cooled laser pump cavity was constructed. A photograph of the pump cavity with the helical lamp and reflector removed is shown in Fig. 4. The helical lamp slides over the dewar.

10 M.P. Vanyukov, et al, Soviet Physics - Doklady 11, 233 (1966)

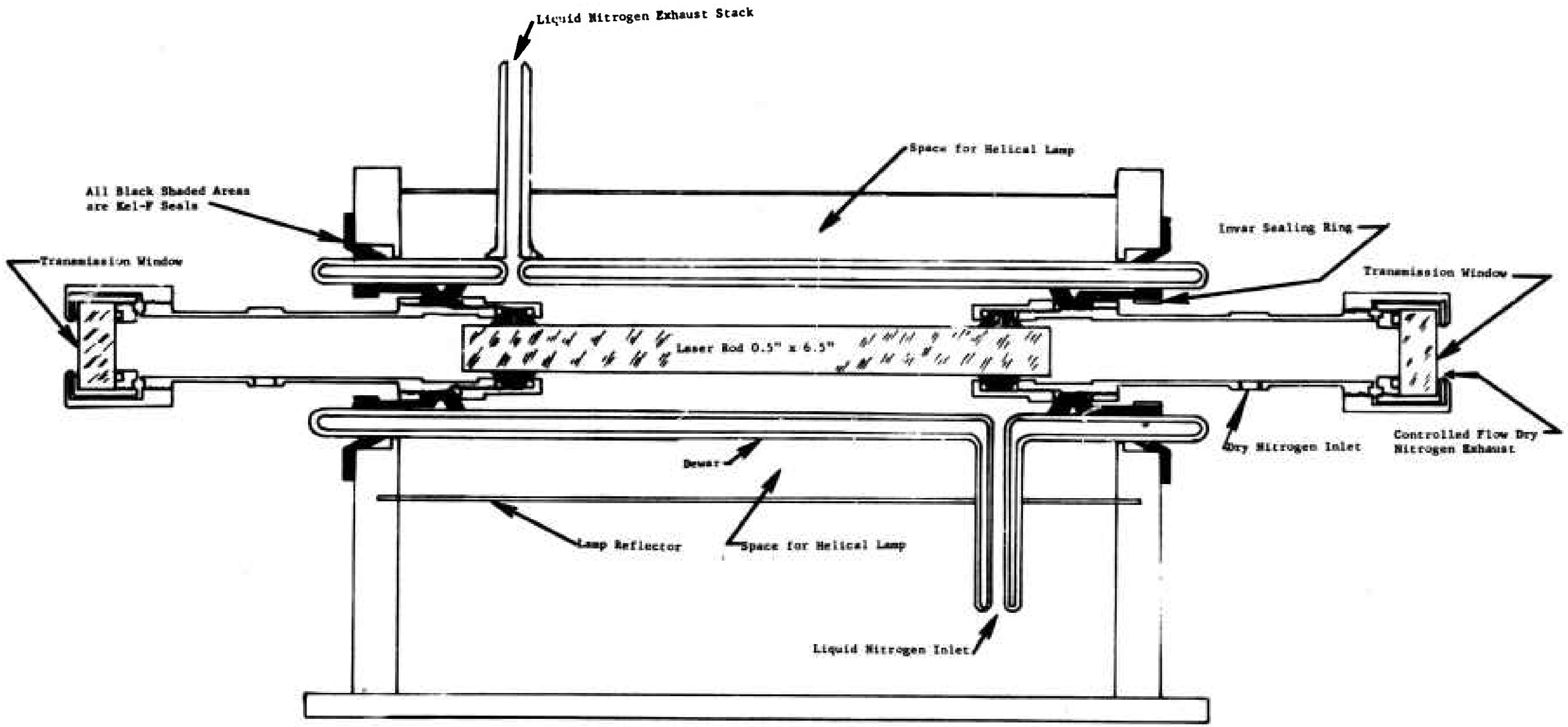


Fig. 3. ***LIQUID NITROGEN COOLED PUMP CAVITY***

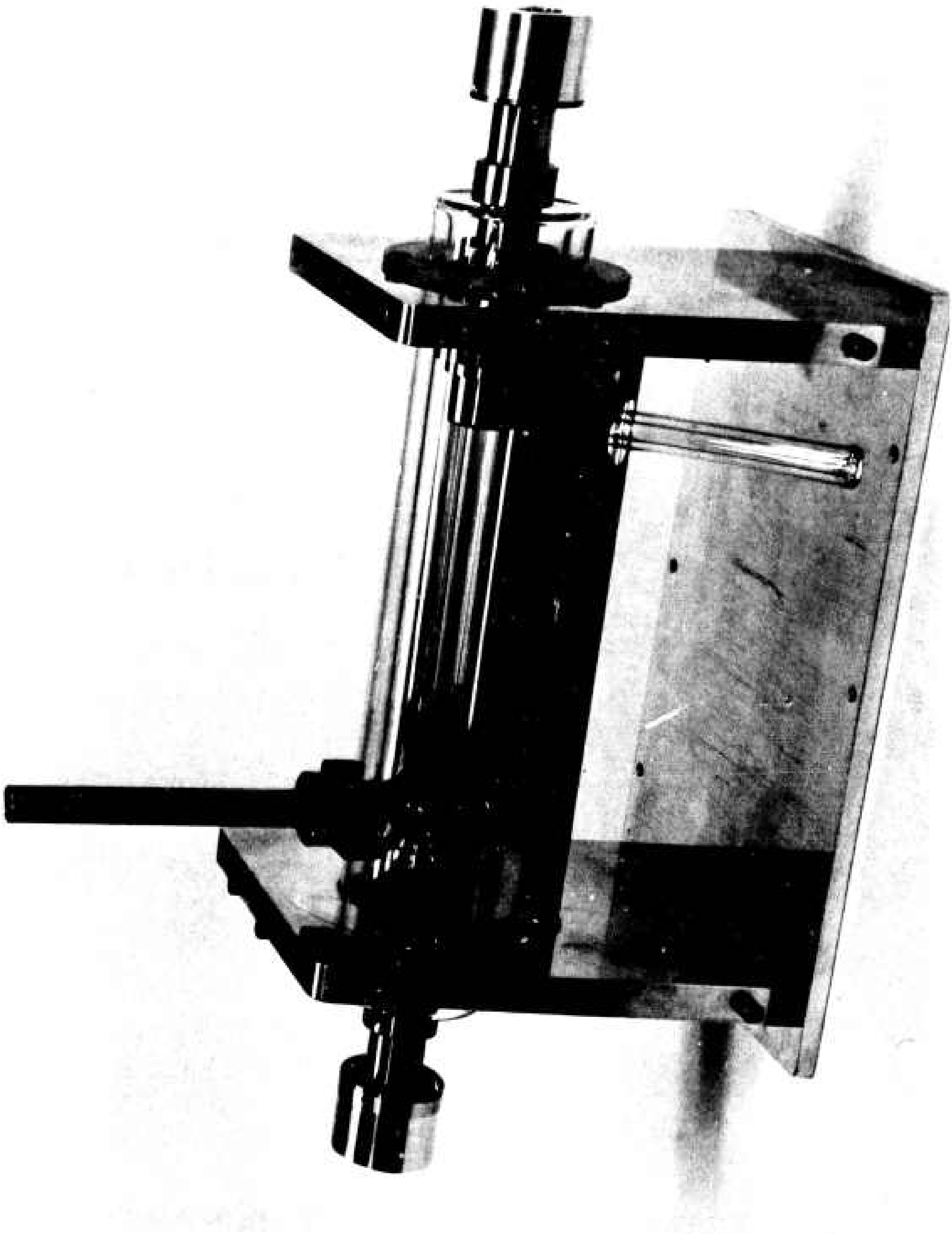


Fig. 4. Liquid Nitrogen Cooled Pump Cavity

Densitometer Measurements

A very sensitive Jarrell-Ash Densitometer which was converted to automatic scanning and recording is used to scan the streak photographs. A photograph of this system is shown in Fig. 5. The streak photographs are made on Polaroid A.S.A. 10,000 and 3,000 film. The densitometer is adjusted to read 100% transmission through the over-exposed film (emulsion plus paper), and zero transmission through an unexposed portion of the film. When using Polaroid film for quantitative measurements it is particularly important to ascertain continually that the exposures are within the very limited dynamic range of the film. Presently, this is monitored by varying the intensity of the probe beam to the camera on different shots with neutral density filters, and also by comparing the densitometer tracings with photodetector traces to check the linearity of the entire streak camera system. A new technique is presently being investigated where the image in the streak camera would be split into two images with one image ten times more intense than the other. These two images would then be recorded side-by-side on one strip of film so that they could be compared for saturation effects of the film.

Trigger Delay Circuitry

Some problems have been encountered with the multiple, variable delay trigger circuitry described in the First Semi-Annual Report. There is some undesired electro-magnetic coupling between the gating elements of the individual delay circuits and certain pulsed components in the system. The circuitry has been made operable under selected delay conditions by additional shielding and filtering in the circuit. Further isolation in the circuitry is required to achieve the greater flexibility in trigger delays necessary to investigate different combinations of laser glass in the three laser pump cavities presently in use.

3. Experiments

The time resolved streak camera and the normal pulse probe have been aligned with the spectrograph and successful streak photographs have been made. Densitometer

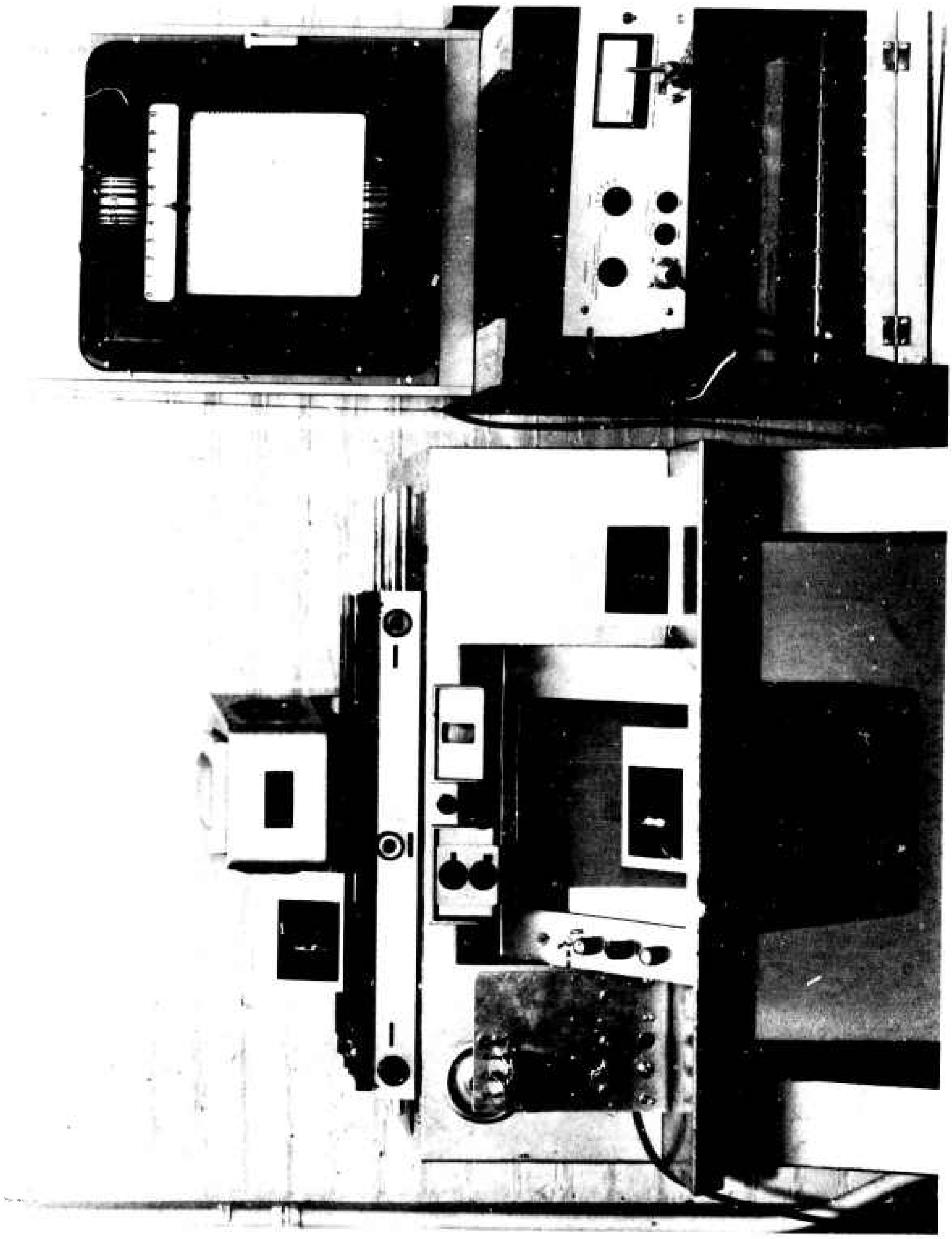


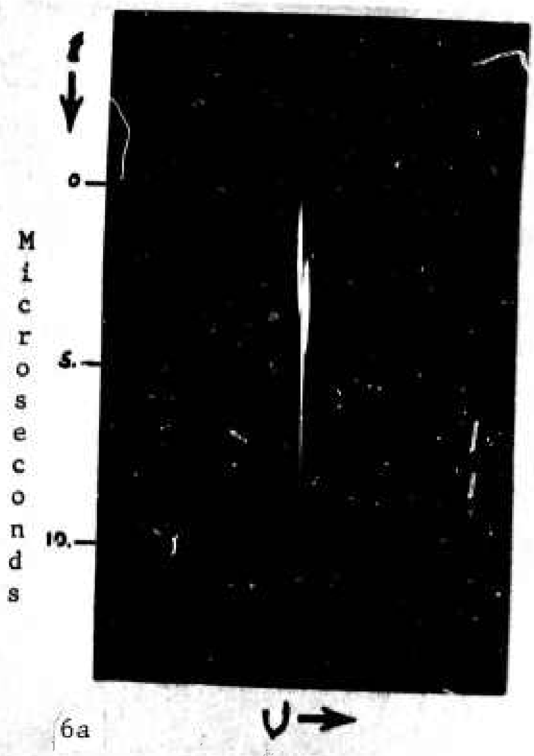
Fig. 5. Photograph of Densitometer

tracings of these laser spikes show they are smoothly shaped in time with a 1 to 10 microsecond duration. The longer duration spikes occur when the laser is pumped near threshold (as seen in Fig. 6a). The best operating condition though is when the probe laser is pumped far above threshold so there are enough spikes that one can make a measurement at some wavelength for every shot. Typical streak photographs are shown in Fig. 6b and c. It will be necessary to take several photographs operating under the same interaction amplifier conditions to get a farily representative statistical record of the cross-relaxation effect as a function of time and frequency. Figures 7 and 8 show the entire system in the present optical configuration from two different directions.

A number of 10 μsec streak photographs have been scanned on the densitometer to study the time behavior of laser spikes with half-widths generally on the order of 1 microsecond. It has been found that the relative shape of each of these spikes for a 500-μsec normal pulse is very nearly identical if their intensities and half-power spike widths are normalized. As can be seen from the graph in Fig. 9, where the normalized time tracings of 3 spikes are superimposed with a 0.5 half-power normalized time, these spikes are alike to within 5% if the tails below 20% power are not included. If the extrapolation time of these representative spikes is limited to significantly less than 1 microsecond by very fast cross-relaxation then the accuracy of this technique should improve from the 5% to 1% or 2%.

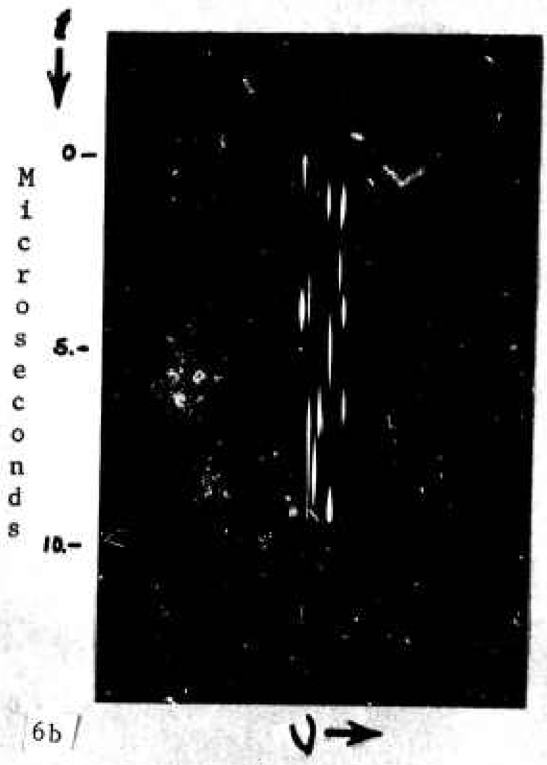
Figure 6

TYPICAL NORMAL PULSE PROBE STREAK PHOTOGRAPHS



6a

Near Threshold



6b

Three Times Threshold

6c

Three Times Threshold
+ 5 dB Interaction
Amplifier Gain

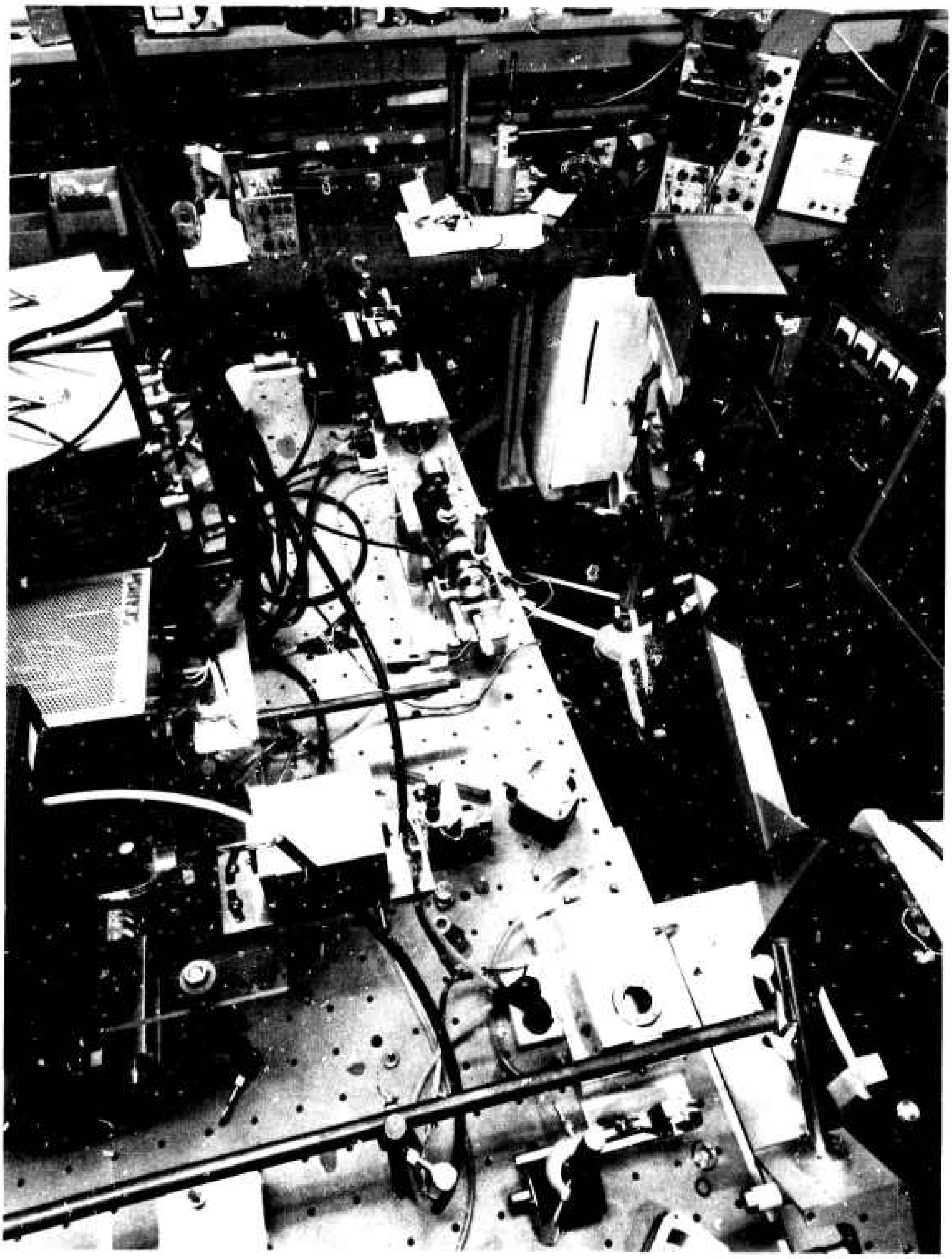


Fig. 7. Photograph of Present System

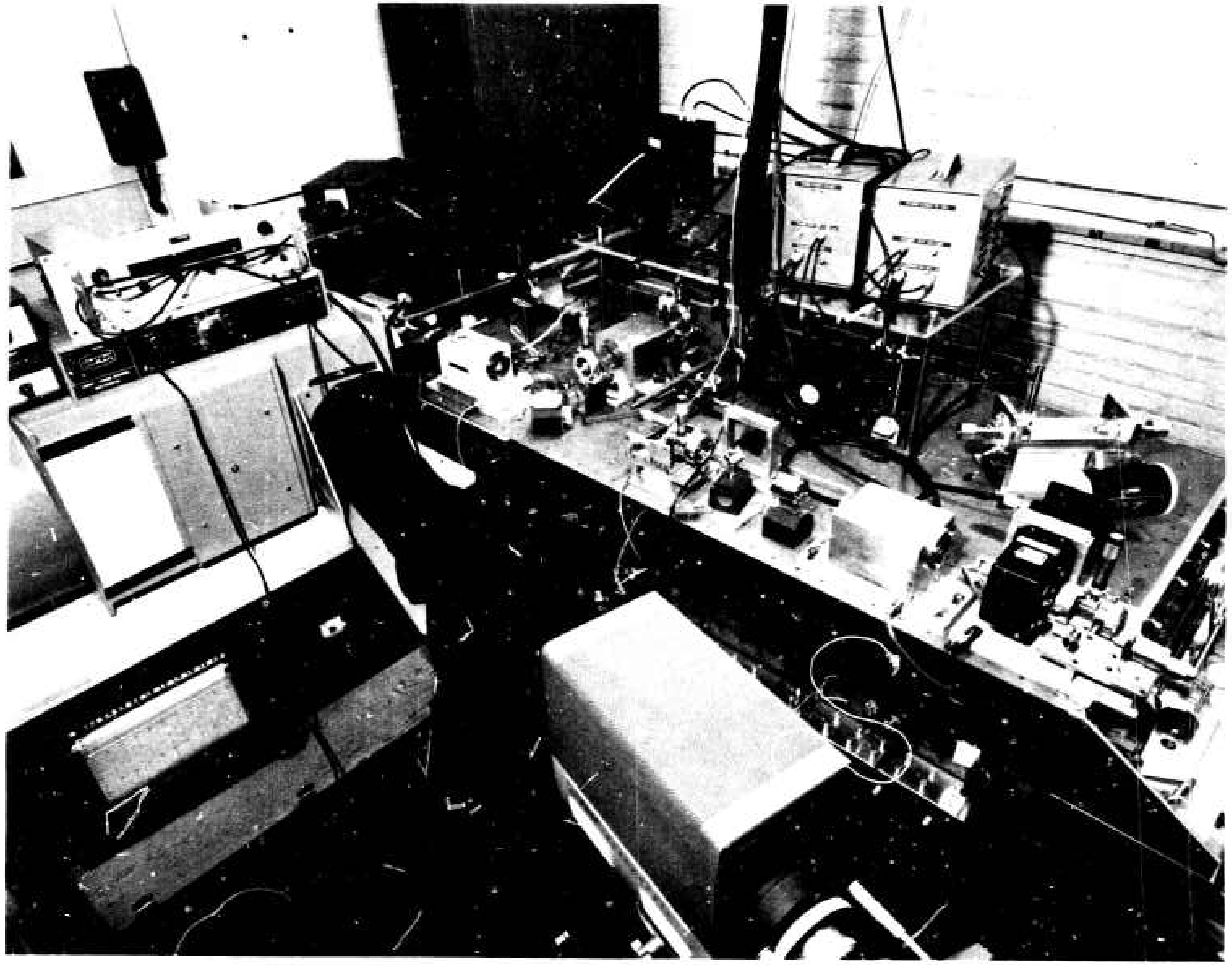
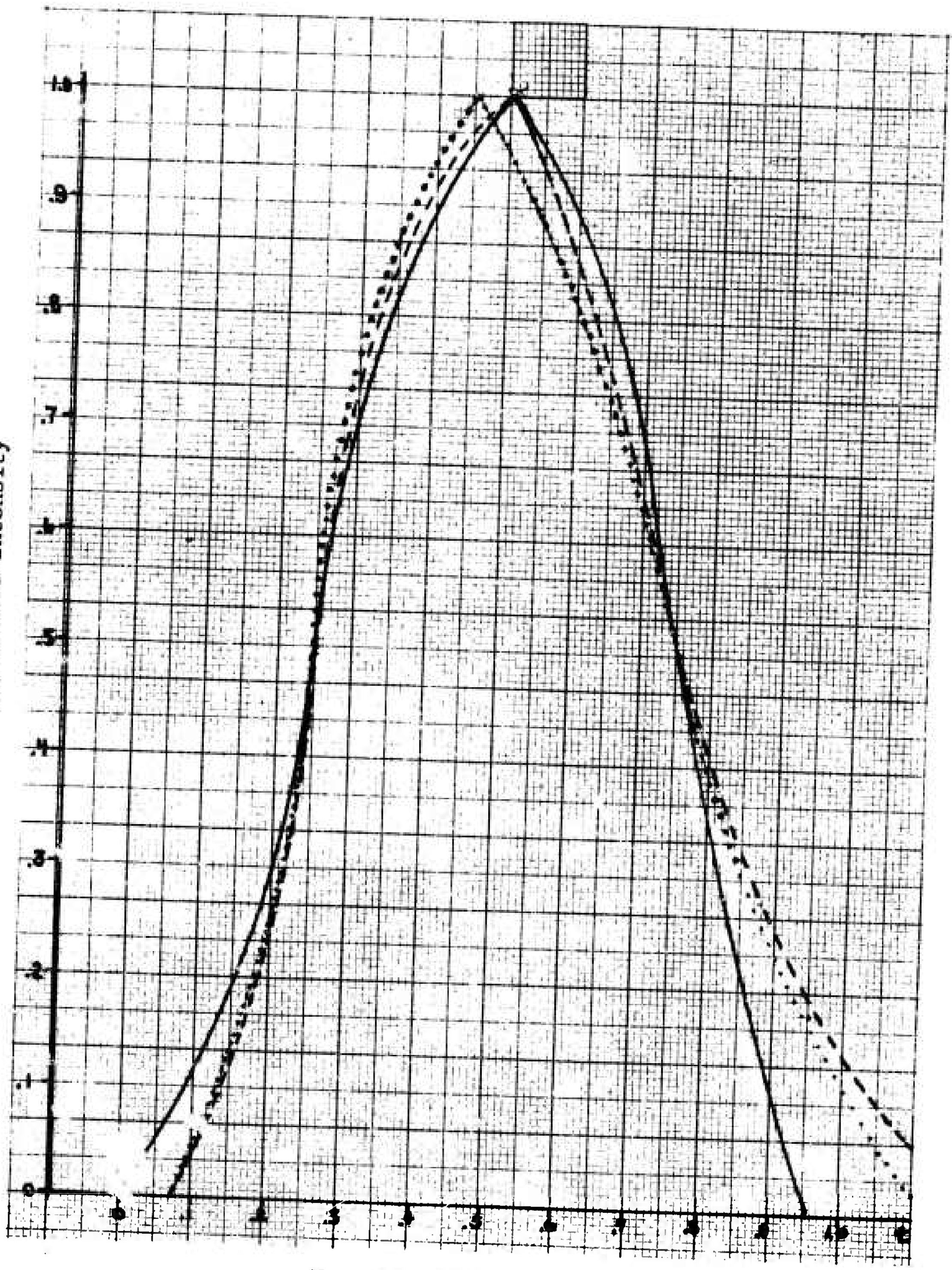


Fig. 8. Photograph Different View of Present System

Fig. 9. Normalized Densitometer Traced Laser Spikes
Superposition of densitometer tracings of three randomly selected laser spikes from one firing of the normal pulse probe. (half-power spike width normalized to 0.5 and intensity maximum normalized to 1.0)



Normalized Time

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13. ABSTRACT

This is a semi-annual report on investigations of cross-relaxation between neodymium ions in laser glass. Work performed during the last six months is described.

Unclassified
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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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